Evaluating the Effect of Steel Fibers on Some Mechanical Properties of Ultra-High Performance Concrete

Cong Thang Nguyen, Huu Hanh Pham, Van Tuan Nguyen, Sy Dong Pham, and Viet Hung Cu

1 Introduction

Over the past few decades, remarkable advances have taken place in research and application of Ultra-High Performance Concrete (UHPC), which outstanding exhibits properties including high flowability, very high compressive strength (usually greater than 150 MPa), high flexural strength (about 15–45 MPa when using steel fiber), very low porosity and excellent durability [1–6]. Therefore, UHPC has become one of the potential and economically efficient materials in specific applications such as thin shell structures, super-high-rise buildings, large span bridges and sustainable structures in marine environment, etc.

UHPC is composed by common materials such as quartz sand with the size of about 100–600 μm, cement, silica fume, water and superplasticizer. The high amount of cement in UHPC, 900–1000 kg/m^3, and very high silica fume (SF) content, 150–250 kg/m^3 (10–30% by weight of cement) [5] with the very low water-to-binder ratio, usually less than 0.25 by mass (Schmidt and Fehling [6, 7] will cause a high shrinkage. This phenomenon gives rise to tensile stress and can cause structural cracking, adversely affecting the properties of UHPC such as permeability, durability, etc. To improve some properties of UHPC, i.e. toughness, homogeneity to withstand the dynamic loads or to limit the crack expansion of the structures, it is necessary to add steel fibers into UHPC. Thanks to that, UHPC is possible can create the thin structures, thereby reducing dead load, increasing efficiency of space used, and

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reducing maintenance costs for projects [8–11]. However, further research is still remained in order to explore this aspect, and it is the target of this research.

This paper present experimental results to evaluate the role of the steel fibers in improving some properties of UHPC such as compressive strength, flexural strength and limiting the cracking expansion.

2 Materials and Methods

2.1 Materials

The materials used in this study are Portland cement PC40 which meets requirements of the Vietnamese standard TCVN 2682:2009; Condensed silica fume (SF) with an amorphous SiO_2 content of 92.3% and its mean particle size of 0.15 μm, reactivity index of SF in excess of 112.5%; Quartz sand with the particle size ranging from 100 to 600 μm; Steel fiber with 13 mm in length, 0.2 mm in diameter and tensile strength of 2750 MPa; Ground Granulated blast furnace slag (GBFS) with a mean particle size of 7.2 μm; and polycarboxylate superplasticizer (SP).

2.2 Methods

The compressive strength test of UHPC was determined according to ASTM C109 with sample size of 50 × 50 × 50 mm [12]. The compression test was done on a hydraulic machine with a load increase of 2.5 kN/s until the sample was damaged.

According to EN 14651, the flexural strength and the relationship between the flexural load and post-cracking behavior of the UHPC sample were carried out on the beam-shaped samples with dimensions of 100 × 100 × 400 mm.

To assess shrinkage cracking tendency in UHPC, an experiment was conducted by the restrained steel ring test according to ASTM C1581-2004. The ring UHPC test samples are 38 mm in thickness, inside diameter of 330 mm, outside diameter of 406 mm, and 152 mm in height. The UHPC mixtures were poured into the steel ring with a thickness of 12.5 mm which is able to counteract concrete shrinkage and leads arising in tensile strains. After 24 h of the casting, the UHPC samples are demolded and cured in the climate chamber (27 ± 2 °C, 50 ± 4% RH) to measure the deformation of the steel ring with the starting time (time zero) being recorded. The upper surface of the UHPC sample is coated with silicon to ensure evaporation of water taking place along the surrounding surface of the test samples.

Table 1 Mix proportion of UHPC mixtures

No.	W/B	S/B	GBFS, %	SF, %	SP, %	Fiber, %
1	0.154	0.85	24	10	1.2	0
2	0.154	0.85	24	10	1.2	1
3	0.154	0.85	24	10	1.2	2
4	0.154	0.85	24	10	1.2	3

2.3 UHPC Compositions

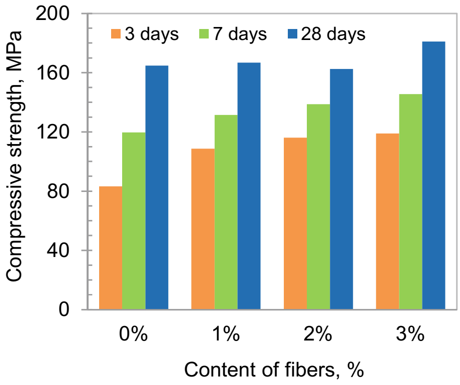
Table 1 shows UHPC mixtures which is used on all of experiments of this study to specific the compressive strength, the flexural strength and the shrinkage resistance. UHPC mixtures were designed with a sand to binder (S/B) ratio of 0.85; the water to binder (W/B) ratio of 0.154. The binder herein is a total of the cement, SF and GBFS. The SF, GBFS and SP are calculated by the weight of the binder, and the weight of steel fiber is calculated by the volume of the UHPC mixture.

3 Results and Discussion

3.1 Effect of the Steel Fiber Content on Compressive Strength of UHPC

Figure 1 shows the effect of the steel fiber content on compressive strength of UHPC. It can be seen that the compressive strength increases with increasing of the steel fiber content. The 28 day-compressive strength of the control sample without the steel

Fig. 1 Effect of the steel fiber content on compressive strength of UHPC



fibers is obtained 164 MPa. When increasing the steel fiber content to 2%, the 28 day-compressive strength of concrete is not changed significantly, i.e. 5% higher compared to that of the control sample. However, when the steel fiber content increases to 3%, the 28 day-compressive strength of concrete is increased significantly, i.e. about 10% higher than that of the control sample, and achieves the maximum value of 180 MPa. This phenomenon can be explained that when the steel fibers are added and disperses into UHPC, a very good bonding on the contact surface between the UHPC substrate and the steel fibers is created. When UHPC is affected by the load, the steel fibers will transfer stress to the UHPC substrate, thus, the formation and development of cracks are limited and the compressive strength increases.

3.2 Effect of Steel Fiber Content on Flexural Strength of UHPC

The influence of the steel fiber content on the UHPC flexural strength is shown in Fig. 2. It can be seen that when the steel fiber content increase, the flexural strength also increases. However, the addition of 1% steel fiber only increases the flexural strength of UHPC slightly, about 44% higher compared to that of the control sample without the steel fibers. When the steel fiber content increases to 2 and 3%, the flexural strength increases significantly, about 66 and 135% higher compared to that of the control sample, respectively. With incorporating 3% steel fibers, the 28 day-flexural strength can be reached the maximum value of 38.8 MPa. It was also observed that the UHPC control sample was devastated immediately after the cracks appears, while the UHPC samples with using the steel fibers were not destroyed suddenly even after UHPC samples appear cracks and the flexural strength continues to be increased.

The addition of the steel fibers not only increases the compressive strength but also limits the expansion of cracks in UHPC. It can be observed that when UHPC control sample is subjected to a load, it can be destructive in the form of brittle materials.

Fig. 2 Effect of the fiber content on flexural strength of UHPC

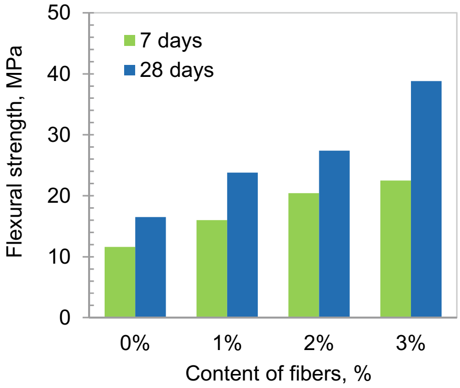
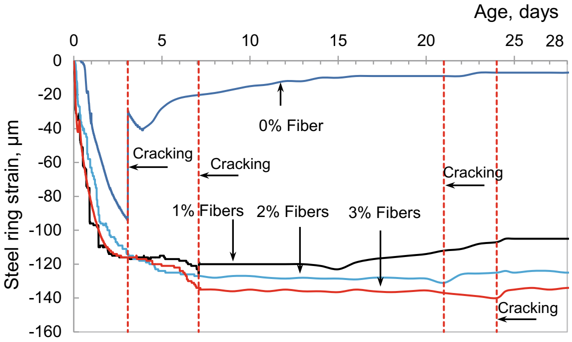


Fig. 3 Deformation of steel rings in restrained shrinkage test



However, when adding the steel fibers, the tight interface bond between these fibers and the UHPC substrate can be considered as a key factor in preventing the steel fibers from being pulled out from the substrate. The steel fibers can also effectively "bridge" between cracks, and transfer the stress to the substrate even when the UHPC sample is cracked, therefore, the flexural strength is increased and the crack formation is also limited. In fact, the improvement of the UHPC's mechanical properties depends on the steel fiber content as well as the type of the steel fiber used.

3.3 *Effect of the Steel Fiber Content on Crack Resistance of UHPC*

In this study, some tests were also carried out using means of restrained ring test to determine the age of UHPC's shrinkage cracking. The experimental results in Fig. 3 shows that for the control samples, the cracks appear after 3 days; but for UHPC samples using 2 and 3% of the steel fibers, the time of occurrence of cracks is 21 days and 24 days, respectively. Therefore, the addition of the steel fibers plays a key role in limiting cracking thereby slowing the process of cracking on concrete structures. When comparing the time of cracking between UHPC control samples without the steel fibers and concrete samples with M35 grade (35 MPa) in the study of Hieu [13], the experimental results showed that, the normal time cracking is 5 days for the normal concrete samples, while the cracking time of the UHPC samples is 3 days. It is important to notice that the UHPC shrinkage is larger than that of the conventional concrete, especially at the early-age. This phenomenon is caused by UHPC using a very high amount of cement and fine mineral admixture, and a very low water to binder ratio. When water in UHPC is lost due to the hydration of cement, also known as self-desiccation phenomenon in hardened cement paste, and due to evaporation of water to the surrounding environment has reduced internal relative humidity of concrete. This process creates the stress in the pores inside the concrete structure, which is considered as the total surface tension on the meniscus surface of the water in the pore system of the concrete, thereby causing shrinkage for the concrete. It should be noted that for UHPC, the process of self-desiccation occurs more strongly at an early age and causes larger shrinkage than that of conventional concrete.

As the normal concrete shrinkage, the restrained UHPC sample through the "restrained ring test" also creates a certain pressure on the steel ring, the so-called actual residual pressure at the surface. The steel ring is considered as the required pressure causing the deformation which is equal to the deformation measured in the steel ring. This pressure is proposed by Hossain and Weiss [14] as follows:

$$\mathrm{P}\ (\mathrm{t}) = -\varepsilon_{\mathrm{steel}}(\mathrm{t}) \cdot \mathrm{E}_{\mathrm{steel}} \cdot \frac{\mathrm{R}_{\mathrm{os}}^2 - \mathrm{R}_{\mathrm{IS}}^2}{2\mathrm{R}_{\mathrm{os}}^2} \tag{1}$$

In which:

P(t)	the interface pressure of the steel ring, MPa
ε_{steel}	the average steel strain
E_{steel}	the elastic modulus of the steel
R_{OS}	the outer radius of the steel ring
R_{IS}	the inner radius of the steel ring.

Once the interface pressure is available, the pressure on the steel ring is caused by the pressure of the UHPC ring sample. Hossain and Weiss [14] also proposed the equation for calculating stress distribution in concrete as follows:

$$\sigma(\mathrm{r}) = -\varepsilon_{\mathrm{steel}}(\mathrm{t}) \cdot \mathrm{E}_{\mathrm{steel}} \cdot \frac{\mathrm{R}_{\mathrm{OS}}^2 - \mathrm{R}_{\mathrm{IS}}^2}{2\left(\mathrm{R}_{\mathrm{OC}}^2 - \mathrm{R}_{\mathrm{OS}}^2\right)} \cdot \left(1 + \frac{\mathrm{R}_{\mathrm{OC}}^2}{\mathrm{R}_{\mathrm{IC}}^2}\right) \tag{2}$$

where:

σ(r)	the inner pressure of the concrete ring sample, MPa
R_{OC}	the outside radius of the concrete ring sample
R_{IC}	the inside radius of the concrete ring sample ($R_{OS} = R_{IC}$).

The concrete pressure is determined by Eqs. (1) and (2) and the relationship lines between the deformation of the steel ring and the time and is shown in Fig. 3. The relationship between the deformation of the steel ring with the concrete stress is shown in Fig. 4. It can be seen that the deformation of the steel ring increases linearly to the concrete pressure. Besides, when the concrete stress increases, the pressure in the steel ring also increases. However, at a certain point when the concrete stress continues to increase and the concrete tensile stress exceeds the tensile strength, the concrete begins to crack.

After that, the concrete stress causes the stress in the steel ring and it will be evenly distributed on the steel ring. The relationship between the steel fiber content and the concrete stress is shown in Fig. 5. From this figure, it can be seen that when increasing the steel fiber content, the concrete stress also increases, at the same time the beginning of cracking in the corresponding concrete increases and the maximum stress of the steel ring can be determined when the concrete cracks corresponding to

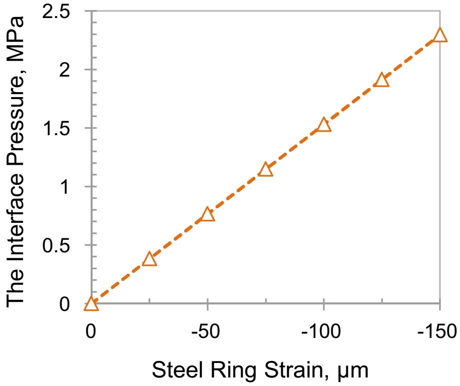


Fig. 4 Pressure of concrete on the steel ring

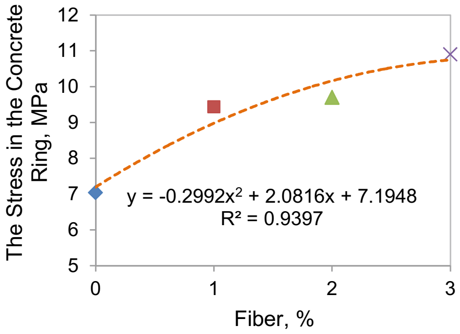


Fig. 5 Maximum stress of steel ring with the different fiber contents used

the steel fiber content used. As a result, the steel fibers have played an important role in limiting cracking and reducing the crack width development for UHPC.

Based on the relationships between the deformation of the steel ring and the time, it also can be seen that for UHPC samples, there is a great reduction of the deformation of the steel ring after cracking. Meanwhile, with UHPC samples using the steel fibers, after appearing cracks, there is no significant decrease in the deformation of the steel ring. At that time, with a tight interfacial bond between the steel fibers and the hardened cement paste, there is the process of transferring stress from the substrate to the fiber, and the bridging effect of the steel fiber through the crack when the cracks appear. Therefore, the steel fibers play a very important role in regulating the process of cracking, they slow down the development of cracks. As the concrete continues to shrink, the cracks also continue to expand, the steel fibers help to redistribute the load in the crack area thereby limiting the propagation of cracks and ensuring the continuity of the structure.

4 Conclusion

Based on the research results of this study, the following conclusions can be drawn:

- The addition of the steel fibers improves both compressive and flexural strength of UHPC, but only significantly with a high amount of steel fiber, i.e. 3%. At 28-day age, it can be achieved a compressive strength of 180 MPa, and a flexural strength of 38.8 MPa, corresponding to about 10 and 135% higher than those of the control sample.
- The addition of the steel fibers has greatly limited the cracking of UHPC due to the shrinkage. For UHPC control sample (without the steel fibers), the time to occur the cracks is 3 days, while UHPC samples using 3% of the steel fibers, this time is up to 24 days. When increasing the amount of the steel fiber, the UHPC pressure on the steel ring increases and the time of the crack appearance is correspondingly slower. Therefore, the addition of the steel fibers plays an important role in increasing tensile strength and limiting cracks thereby slowing the process of formation and development of cracks for UHPC structures.

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